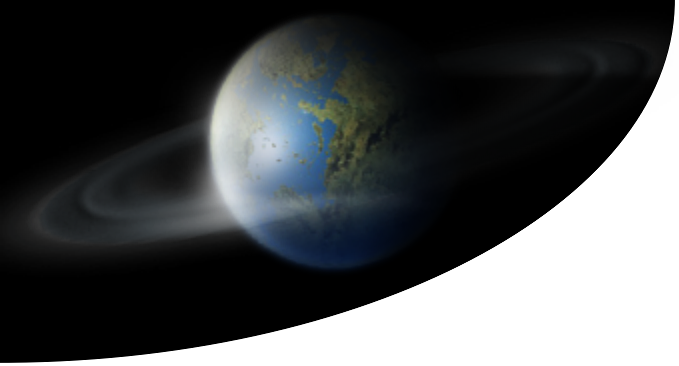

Exoplanet Direct Imaging SAGs

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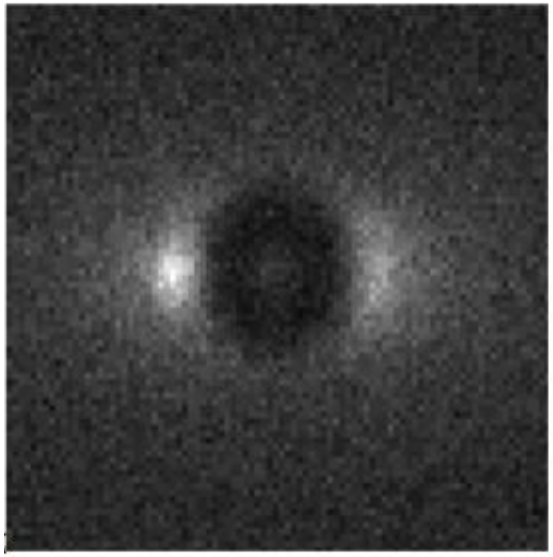


Nearby Earth in 1 zodi disk near 2λ/D (Guyon et al. 2009)

ExoPAG 7 – Long Beach CA
5 January 2013

Overview

- SAG 5 is devoted to requirements for a flagship-class direct imaging mission
- A new focus on smaller missions is warranted
  - Diminished expectations for technology and mission funding
  - Exploring a new 2.4m opportunity (AFTA)
- We are planning to form a new SAG to do the same for “moderate” direct imaging mission concepts
  - Probe class ($1B) and 2.4 m options will be prominent
- The proposed SAG 9 for moderate direct imaging will draw heavily from the work done in SAG 5
- Participation in SAG 9 again will be by self-nomination (volunteering)

SAG 5 Membership

- Tom Greene and I are co-chairs. Marie Levine (JPL) is Facilitator.
- ~ 60 scientists, technologists, engineers
- Communicating via http://tech.groups.yahoo.com/group/exopag_flagship/

L name	F name	email	Institution	Interests / Expertise	SAG Task area
Apai	Daniel	apai@as.arizona.edu	UA	Ground-based imaging searches / characterization	
Augereau	Jean-Charles	augereau@obs.ujf-grenoble.fr	IPAG Grenoble	debris disks and exozodiacal dust disks, SPICES concept	dust, planet imaging
Belikov	Rus	ruslan.belikov-1@nasa.gov	NASA ARC	coronagraph technology	
Booth	Jeff	jeffrey.t.booth@jpl.nasa.gov	JPL	Mission architectures	
Breckinridge	Jim	jbreckin@caltech.edu	CIT (adjunct)	Planet imaging telescopes and technologies	
Cahoy	Kerri	kerri.cahoy@gmail.com	MIT / NASA GS	Planetary atmospheres, mission design, DRMs	Science, DRM, mission trades
Cash	Webster	wcash@origins.colorado.edu	Univ Colorado	Science measurements, DRMs, occulters, technology	occulter
Chakrabarti	Supriya	supc@bu.edu	Boston Universi	Technology	
Clampin	Mark	mark.clampin-1@nasa.gov	NASA GSFC	coronagraph science and technology (VNC)	coronagraph
Defrere	Denis	ddefrere@mpifr-bonn.mpg.de	MPIfR Bonn	Imaging exozodiacal disk structures in Hzs and impact on planet imaging	Science
Glassman	Tiffany	Tiffany.Glassman@ngc.com	Northrop Grumm	Starshades / science requirements	occulter
Greene	Tom	tom.greene@nasa.gov	NASA ARC	observations, technology, DRM	editor and co-chair
Guyon	Olivier	guyon@naoj.org	UA / Subaru	coronagraph science and technology (PIAA)	coronagraph
Kaltenegger	Lisa	lkaltene@cfa.harvard.edu	CfA /MPIA	Earth-like atmospheric spectra	Science
Kasdin	Jeremy	jkasdin@Princeton.EDU	Princeton	coronagraphs, occulters, system engineering	occulter and coronagraph
Krist	John	john.krist@jpl.nasa.gov	JPL	coronagraph design & modelling, debris disk imaging	Modeling requirements, post-observation reduction
Levine	Marie	marie.b.levine-west@jpl.nasa.gov	JPL	Technology, observatory system design, requirements & analysis	system engineering
Lilly	Chuck	chuck.lillie@ngc.com	Northrop Grumm	Architecture issues, technology	Occulter & coronagraph
Lisman	Doug	p.d.lisman@jpl.nasa.gov	JPL	coronagraphs, occulters, system engineering	occulter and coronagraph
Lisse	Carey	Carey.Lisse@jhuapl.edu	JHU APL	exosystem spectroscopy / materials characterization	Science
Lo	Amy S	Amy.Lo@ngc.com	NGAS	Science measurements, DRMs, occulters, performance modeling, technology, ground testing	occulter
Lyon	Rick	richard.g.lyon@nasa.gov	GSFC	Flow of requirements into architectures	requirements to architectures
Mandell	Avi	Avi.Mandell@nasa.gov	NASA GSFC	IR spectral characterization of exoplanets	Science
Marley	Joe	joseph.h.catanzarite@jpl.nasa.gov	JPL	Science measurements, astrometry	Science
Marley	Mark	mark.s.marley@nasa.gov	NASA ARC	Planetary atmospheres and giant planet spectra	Science
McElwain	Michael	michael.w.mcelwain@nasa.gov	NASA GSFC	coronagraphy, wavefront control, and IFU spectroscopy and science policy	Science and technology
Noecker	Charley	mcnoecke@ball.com	Ball ATC	Science measurements, DRMs, coronagraphs, occulters, control systems, performance modeling, technology, ground testing	editor and co-chair, occulter and coronagraph, system engineering
Petit	Pascal	petit@ast.obs-mip.fr	Observatoire Mi	stellar magnetic activity via spectroscopy and spectropolarimetry	Science
Pitman	Joe	joe.pitman@exsci.org	ExSci	space telescopes, SE, modeling & simulation, I&T, verification	Strawman concepts and requirements
Postman	Marc	postman@stsci.edu	STScI	Large UV/O mission synergy	Large UV/O mission synergy
Redding	Dave	david.c.redding@jpl.nasa.gov	JPL	integrated modeling	system engineering
Roberge	Aki	aki.roberge-1@nasa.gov	NASA GSFC	Exozodi	Exozodi SAG lead
Serabyn	Gene	eserabyn@jpl.nasa.gov	JPL	Science, coronagraphs, interferometers	ultimate contrast, wavelengths, IWA
Shaklan	Stuart	stuart.b.shaklan@jpl.nasa.gov	JPL	architecture issues	occulter and coronagraph
Shao	Mike	michael.shao@jpl.nasa.gov	JPL	Planet / dust / speckle discrimination, astrometry, coronagraph (VNC)	Science and coronagraph
Smith	Erin C.	erin.c.smith@nasa.gov	NASA ARC	(Occulters)	occulter
Solmaz	Arif	arif.solmaz@gmail.com	Turkey (student)	Transits, exoplanets	
Soummer	Rémi	soummer@stsci.edu	STScI	Science measurements, coronagraphs, occulters	occulter and coronagraph
Sparks	Bill	sparks@stsci.edu	STScI	Biosignatures, circ. Polarization	Science, instrument concepts
Stapelfeldt	Karl	krs@exoplanet.jpl.nasa.gov	JPL	Science performance modeling, targets, dust	Science
Tanner	Angelle	angelle.tanner@gmail.com	Georgia State	target selection, astrometry, high contrast imaging	Science / targets
Tenerelli	Domenick	domenick.tenerelli@lmco.com	LMMSC	coronagraph and occulter missions and technologies	occulter and coronagraph
Trauger	John	John.Trauger@jpl.nasa.gov	JPL	coronagraph and wavefront control technologies	Mission design and performance simulations
Tsvetanov	Zlatan	zlatan@pha.jhu.edu	JHU	observations, science requirements, figures of merit	Science
Turnbull	Maggie	turnbull.maggie@gmail.com	Global Science	Target star characteristics, background objects	Science
Vanderbei	Robert	rvdb@Princeton.EDU	Princeton	Coronagraphs and Occulters	
Vosteen	Amir	amir.vosteen@tno.nl	TNO	nulling interferometry, systems engineering.	
Williams	Darren	dmw145@psu.edu	PSU	Earth-like moons of giant exoplanets	Science

Task Description

- Coronagraph and Occulter SAGs were combined into SAG 5 after ExoPAG 3 (Jan 2011)
- Develop strawman science requirements for direct imaging
  - Groundwork for Astro2010 mid-decade technology downselect
  - Structured to support making comparisons and decisions

1. Start on a "flagship" direct imaging mission in 2020+

   Flagship ≡ very likely to find & characterize at least one Earth-like planet in the habitable zone of its star

2. Then consider smaller mission(s) along that path

- Meetings with COPAG → initiated effort to define a shared space telescope for exoplanets and UV-opt astrophysics
  - COPAG's flagship definition is consistent with ours

SAG 5 Progress 2011-12

- Established a framework of Science Goals, Objectives, and Musts & Discriminators
  - See description on next page
  - Discussed via email, telecons, and at ExoPAG meetings
- Flagship class mission, COPAG partnership
  → Emphasized terrestrial planets
  - Super-earths, giant planets, and debris disks are included in key Discriminators (ranking criteria)
- We have finished this work with some caveats:
  - We will not assign scoring at this time
  - Several requirement values are TBR, pending better knowledge
    - Prevalence of Earth-like exoplanets ($\eta_{\oplus}$) from Kepler
    - Exozodi statistics (brightness and profile) from LBTI or elsewhere
- This is our final report
- Move on to smaller missions (proposed SAG 9)

Unusual Framework for Requirements

- We have articulated

3 overarching science goals → 11 more specific science objectives → 13 Musts (minimum capability) / 14 Discriminators (valuable additions)

- **Musts** correspond to traditional minimum science requirements, but can include technical or programmatic constraints
- **Discriminators** are criteria for scoring/ranking — a new way to handle Baseline and Goal/Stretch requirements
  - Phrased to be independent of mission architecture
- Allows fair comparison of different mission concepts with very different strengths and weaknesses
- Worked with SAG 4 (exoplanet characterization) and SAG 1 (exozodi requirements) in developing these lists
- COPAG has agreed to formulate their requirements in this framework
  ➔ Selection of one mission concept based on the union of both sets of criteria

Science Goals (Top Level)

- Goal1: **Determine the overall architectures** of a sample of nearby planetary systems. This includes determining the numbers, brightnesses, locations, and orbits of terrestrial to giant planets and characterizing exozodiacal dust structures in regions from habitable zones to ice lines and beyond. This information will also provide clues to the formation and evolution of these planetary systems.
- Goal 2: **Determine or constrain the atmospheric compositions** of discovered planets, from giants down to terrestrial planets. Assess habitability of some terrestrial planets, including searching for spectral signatures of molecules and chemical disequilibrium consistent with the presence of life. Determining or constraining surface compositions of terrestrial planets is desirable but is not strictly required.
- Goal 3: Determining or constraining **planetary radii and masses are stretch goals** of this mission. These are not strictly required. However, measuring radii and masses would provide a better understanding of detected planets, significantly increasing the scientific impact of this mission.

What were the drivers that took us this way?

- Multiple competing concepts for the exoplanet mission
  ➔ Blizzard of options in play
  - Confusing conflicted story to the Decadal Committee
- A need to downselect to one concept in mid-decade
  ➔ Decisions!
  - Show clarity and unity for the review committee
- Fuzzy information
  - Heterogeneity of concepts makes the decision baffling
  - Scarce funding for technology development leads to a decision based on inadequate information
- Flagship class → Terrestrial exoplanets
  - “Rich” capability
  - Exoplanet sensitivity surpassing all previous exoplanet searches

Vector from SAG 5 to proposed SAG 9

- How would we modify those goals for a smaller mission?
  - More modest sensitivity, angular separation
    - Giant outer planets
    - Exozodi clouds
  - Prior ground-based detection of targets
  - Ground-based characterization

- Let’s look at some examples…

Science Goals

A. Minor relaxation

- Goal1: **Determine the overall architectures** of a sample of nearby planetary systems. This includes determining the numbers, brightnesses, locations, and orbits of ~~terrestrial to giant~~ planets and characterizing exozodiacal dust structures in regions from habitable zones to ice lines and beyond. This information will also provide clues to the formation and evolution of these planetary systems.
- Goal 2: **Determine or constrain the atmospheric compositions** of discovered planets, ~~from giants down to terrestrial planets. Assess habitability of some terrestrial planets, including searching for spectral signatures of molecules and chemical disequilibrium consistent with the presence of life.~~ Determining or constraining surface compositions of terrestrial planets is desirable but is not strictly required.
- Goal 3: Determining or constraining **planetary radii and masses are stretch goals** of this mission. These are not strictly required. However, measuring radii and masses would provide a better understanding of detected planets, significantly increasing the scientific impact of this mission.

Science Goals

B. Leave unchanged

Several of these goals are likely too difficult for small missions, but there's no need to constrain ambition at the beginning

- Goal1: **Determine the overall archite**
  planetary systems. This includes dete
  brightnesses, locations, and orbits of t
  characterizing exozodiacal dust struct
  zones to ice lines and beyond. This in
  clues to the formation and evolution o
- Goal 2: **Determine or constrain the a**
  discovered planets, from giants down
  habitability of some terrestrial planets,
  spectral signatures of molecules and c
  consistent with the presence of life. Determining or constraining surface compositions of terrestrial planets is desirable but is not strictly required.
- Goal 3: Determining or constraining **planetary radii and masses are stretch goals** of this mission. These are not strictly required. However, measuring radii and masses would provide a better understanding of detected planets, significantly increasing the scientific impact of this mission.

Science Objectives (condensed)

1. Detect terrestrial planets
2. Measure orbital parameters
3. Obtain multi-band photometry
4. Confirm planets and distinguish among them (motions & colors)
5. Determine or constrain planet masses if possible
6. Spectroscopic characterization of terrestrial planets
7. Detect giant planets
8. Spectroscopic characterization of giant planets
9. Measure location and extent of dust disks
10. Detect and measure substructures in dusty disks to infer planets
11. Understand the evolution of circumstellar disks: pre-planetary to debris

Detailed language

Science Objectives

A. Minor relaxation

1. Detect ~~terrestrial~~ planets
2. Measure orbital parameters
3. Obtain multi-band photometry
4. Confirm planets and distinguish among them (motions & colors)
5. Determine or constrain planet masses if possible
6. Spectroscopic characterization of ~~terrestrial~~ planets
7. ~~Detect giant planets~~

Redundant

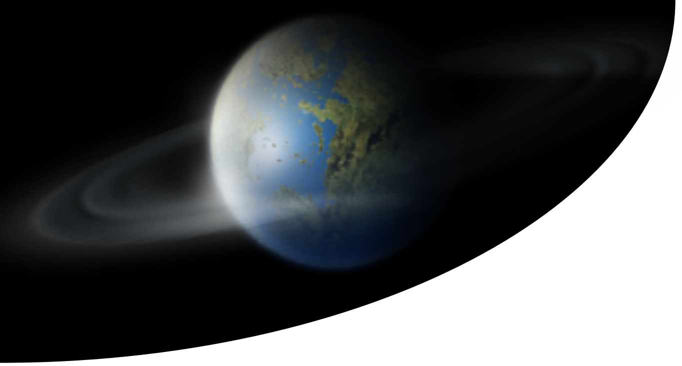
8. ~~Spectroscopic characterization of giant planets~~
9. Measure location and extent of dust disks
10. Detect and measure substructures in dusty disks to infer planets
11. Understand the evolution of circumstellar disks: pre-planetary to debris

Detailed language

Musts and Discriminators

- Explained briefly in backup slides
- Described in detail in draft report (available on request)

- Musts and Discriminators are where we'll make the most extensive changes between SAG 5 and SAG 9



We welcome your comments

Please join us

Science Objectives (full text, 1/4)

1. Directly detect terrestrial planets that exist within the habitable zones around nearby stars or, alternatively, observe a large enough sample of nearby systems to show with high confidence that terrestrial planets are not present.
2. Measure or constrain orbital parameters (semi-major axis and eccentricity) for as many discovered planets as possible, especially those that show evidence of habitability.
3. Obtain absolute photometry in at least three broad spectral bands for the majority of detected planets. This information can eventually be used, in conjunction with orbital distance and planet radius, to constrain planetary albedos.

Return

Science Objectives (full text, 2/4)

4. Distinguish among different types of planets, and between planets and other objects, through relative motion and broadband measurements of planet color.
5. Determining or constraining planetary masses is highly desired but not required. Determining masses would allow estimates of planetary radii to be made, thereby enabling calculation of planetary albedos (Objective 3).
6. Characterize at least some detected terrestrial planets spectroscopically, searching for absorption caused by O_2, O_3, H_2O, and possibly CO_2 and CH_4. Distinguish between Jupiter-like and H_2O-dominated atmospheres of any super-Earth planets. Such information may provide evidence of habitability and even of life itself. Search for Rayleigh scattering to constrain surface pressure.

Return

Science Objectives (full text, 3/4)

7. Directly detect giant planets of Neptune's size or larger and having Jupiter's albedo in systems searched for terrestrial planets. Giants should be detectable within the habitable zone and out to a radius of at least 3 times the outer habitable zone radius .
8. Characterize some detected giant planets spectroscopically, searching for the absorption features of CH_4 and H_2O. Distinguish between ice and gas giants, as well as between Jupiter-like and H_2O-dominated atmospheres of any mini-Neptune planets.
9. Measure the location, density, and extent of dust particles around nearby stars in order to identify planetesimal belts and understand delivery of volatiles to inner solar systems.

Return

Science Objectives (full text, 4/4)

10. In dusty systems, detect and measure substructures within dusty debris that can be used to infer the presence of unseen planets.
11. Understand the time evolution of circumstellar disk properties around a wider star sample at greater distances, from early protoplanetary stages through mature main sequence debris disks.

- The Science Goals and Objectives are related as follows

Science Goals	Science Objectives										
	1	2	3	4	5	6	7	8	9	10	11
1. Architectures	✓	✓		✓	✓		✓		✓	✓	✓
2. Compositions			✓	✓	(✓)	✓		✓			
3. Masses & radii			✓	✓	✓					✓	

Return

Musts (full text, 1/5)

<u>Pass/Fail bare minimum requirements</u> for a mission to be worthy of the effort & expense.
<u>All candidate mission concepts must meet these criteria.</u>

1. Able to detect an Earth twin at quadrature in a Solar System twin at a distance of 10 pc
   - *Rationale:* "Pushpin" in the middle of the performance range required by M3. That is, any observatory able to meet M3 should naturally meet this as well.
   - *Comment:* Not a driving requirement, but helpful to communicate with NASA and taxpayers.
2. Able to detect a Jupiter twin at quadrature in a Solar System twin at a distance of 10 pc
   - *Rationale:* "Pushpin" in the middle of the performance range required by M3.
   - *Comment:* Not a driving requirement, but helpful to communicate with NASA and taxpayers.
3. Examine at least 14 CumHZs to detect point sources with TXP sensitivity
   - *Rationale:* Matches the STDT's Requirement 3 for a minimum mission (§1.4.2), with optimistic $\eta_\oplus$=20%. We chose this case for the Musts, so that a less capable mission can still pass the Musts and be considered. This case also yields >95% probability of seeing at least one TXP assuming $\eta_\oplus$=20%, and also offers a good chance of seeing several TXPs.
     NB: the performance needed here is sufficient to detect many giant planets outside the HZ.
   - *Comment:* If $\eta_\oplus$=20%, the expected value of the number of TXPs detected is 2.8. The probability of seeing at least one TXP is >95%
     NB: our "optimistic" $\eta_\oplus$ is supported by a preliminary analysis of the Kepler data, which argues for a value of more than 30%.

Musts (full text, 2/5)

4. Examine at least 3 (TBR) CumIHZs to detect point sources with TXP sensitivity
   – *Rationale:* We want to ensure that not all of the partial HZs examined are in the outer HZ, 1-2 AU (EID).
   – *Comment:* 3 was chosen semi-arbitrarily; this warrants more thought, and a capability assessment. At least we would like this number of CumIHZs to be naturally consistent with the capability of a mission that is sized to meet M3 above, assuming a reasonable distribution of SMA within the HZ.
5. Characterize every discovered candidate exoplanet by R>=4 spectroscopy (color photometry) across a passband from 0.5 μm to the maximum feasible wavelength less than 1.0 μm.
   – *Rationale:* Require instrumentation and time allocation to attempt this measurement on every planet found, large or small. Long wavelengths may be unreachable due to IWA or red leak.
6. Able to characterize the "Earth" in a Solar System twin at 5 pc (TBR) and the "Jupiter" in a Solar System twin at 10 pc by R>70 spectroscopy across 0.5-1.0μm
   – *Rationale:* Require instrumentation and enough observing time for one such measurement. Assume favorable conditions in which IWA and brightness are not a limitation. We expect the mission to see "Jupiter" easily.
   – *Comment:* Pushpin for hypothetical optimistic case. Not all found planets will be reachable by spectroscopy to 1.0μm because of IWA limitations; but if IWA scales with λ, then detection at 10 pc at λ=0.5μm is equivalent to 5 pc at λ=1.0μm.
   The 10 pc distance chosen for Jupiter is fairly arbitrary, not challenging in photometry or IWA. Its purpose was just to make a requirement for outer giant planet spectroscopy.
   – NB: for some mission concepts, IWA is approximately independent of wavelength across a wide range.

Musts (full text, 3/5)

7. Able to determine the orbital SMA to 10% for the "Earth" in a Solar System twin at 6.5 pc
   - *Rationale:* Like in STDT §1.4.2 (4)
   - *Comment:* Pushpin for hypothetical optimistic case. We declare that this knowledge has value, but our intent at this time is that IWA will not be the main challenge; it just requires instrumentation for star-planet angle measurements, and an adequate observing strategy. The 6.5 pc distance is fairly arbitrary in meeting that intent.
8. Able to measure O_2 A-band equivalent width to 20% for the “Earth” at elongation in a Solar System twin at 6 pc.
   - *Rationale:* Establish measurement sensitivity to a key biomarker spectroscopic signature.
   - *Comment:* If IWA scales with λ, and the planet can be detected at 10 pc at λ=0.5μm, then it can be detected at 6 pc at λ=0.83μm, which is sufficient to span the O_2 A-band at λ=0.76μm.
9. Able to measure H_2O equivalent width to 20% for the “Earth” at elongation in a Solar System twin at 5 pc and the CH_4 equivalent width in a “Jupiter” in a Solar System twin at 10 pc.
   - *Rationale:* Establish measurement sensitivity to a key biomarker spectroscopic signature. Was not included in STDT §1.4.2, but it could be assuming IWA scales proportional to λ.
   - *Comment:* If IWA scales with λ, and the planet can be detected at 10 pc at λ=0.5μm, then it can be detected at 5 pc at λ=1μm, which is sufficient to span the H_2O band at 0.94μm. Likewise, there is a strong CH_4 band at 0.89μm, which we expect to be accessible at 0.5" working angle.

Musts (full text, 4/5)

10. Conduct a search that has at least 85% (TBR) probability of finding at least one TXP
<u>and</u> measuring its color at R=4
<u>and</u> measuring its SMA with 15% uncertainty (TBR)
<u>and</u> measuring its spectrum (0.5-0.8μm)(TBR) with R≥70 and 20% (TBR) spectrophotometric uncertainty.
    - *Rationale:* The combination of several key measurements on one planet. This is full of TBRs, which will require a lengthy analysis to resolve; but it illustrates a tasty minimum likelihood of finding and coarsely-but-fully characterizing a TXP. This implicitly constrains search depth, time allocation, and characterization capability.
    - *Comment:* This is much more difficult than M3—being able to measure color, SMA, fine spectrum to 0.8μm, and 20% photometry all on the same TXP. If we don't scale back the parameters in this case, the observatory will be driven strongly by this requirement, and likely go well beyond the other requirements. We still don't know that a planet exists with characteristics that are favorable for all of these measurements together, so we can't assemble requirements that will get that one planet; but again we can substitute probabilities for the scientific unknowns ($\eta_\oplus$ and orbit/IWA), and then estimate the statistical likelihood of it for any mission concept.
11. Absolute photometry of "Earth" at maximum elongation in a Solar System twin at 8 pc to 10%
    - *Rationale:* Like in STDT §1.4.2 (6), which refers to an Earth twin in a Solar System twin at 8 pc. Pushpin to fix a calibration requirement

Musts (full text, 5/5)

12. Able to guide on the central star as faint as V_{AB}=16 (TBR) for high contrast imaging at degraded sensitivity.
    - *Rationale:* Contrast for disk science is not as demanding as for TXP science, but generally demands a wider range of stars, often much fainter than TXP target stars.
    - *Comment:* We need further conversation with the SAG 1 team (characterization of exozodi disks). We hope this will also prompt a capability assessment. We are hoping for graceful degradation of coronagraphy with central star magnitude. A goal is sensitivity to mag 30 point sources in the neighborhood of a star of any magnitude.
13. Capable of high-contrast optical imaging of extended structures with surface brightness sensitivity of (TBD of the star) at > TBD arcsec from the central star.
    - *Rationale:* Disk science
    - *Comment:* We need further conversation with the SAG 1 team (characterization of exozodi disks). Probably need a few such benchmarks on a curve.

- N.B. there are no Musts for a <u>number</u> or <u>percentage</u> of confirmed exoplanets.
  - Confirmation is a knotty problem, not well understood, and it may prove too big a challenge for the first mission we can afford. We would still get a list of exoplanet candidates and a significant scientific and technical step forward.

Musts mapped to Objectives

	Science Objectives										
Musts	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
M1: detect Earth twin	✓										
M2: detect Jupiter twin							✓				
M3: 14 CumHZs	✓						✓				
M4: 3 CumIHZs	✓						✓				
M5: colors			✓	✓				✓			
M6: fine spectra						✓		✓			
M7: orbital SMA	✓	✓		✓							
M8: oxygen						✓					
M9: water						✓		✓			
M10: all on 1 planet	✓	✓	✓	✓		✓					
M11: absol photometry			✓								
M12: guide on faint star									✓	✓	✓
M13: surface brightness									✓	✓	✓

Return

Discriminators

- Discriminators are not pass/fail but numerically scored criteria, based on Metrics which are
  - Quantitative or semi-quantitative,
  - Well-defined and unambiguous
    - observatory mass, number of launch vehicles, number of science observations in 5 years, etc.
  - Defined in a way that is applicable to all concepts
  - Complete enough to allow each mission concept to accrue points for all of its strengths
- Scores are rooted in the metrics, but are a layer of abstraction from them
  - Many Discriminators can be considered all together, even if they're of a wildly different nature
  - Scores ideally developed by consensus, but often fairly subjectively
- Weights are also developed by consensus,
  - They reflect the relative importance of each Discriminator to the outcome of the mission.
  - Each Discriminator has a numerical weight which applies to all concepts for that Discriminator
  - For each concept, a dot-product of the column of scores with these weights yields a single number, a composite score for the concept, which is the basis for choosing a mission concept
- Scores and weights are both subjective, but subject to experiments:
  - We will conduct extensive tests of fiddling with these numbers to see how sensitive the final conclusion is to minor changes
  - When we are comfortable that the decision rests on judgments that we all believe, we are ready to report a decision with confidence

Discriminators (full text, 1/5)

1. Number of CumHZs searched to TXP sensitivity
   - *Rationale:* Beyond the minimum in M3, we want a deeper search (more CumHZs) to get more planets
   - *Comment:* An earlier version of this requirement specified a minimum δ-mag, but this was deemed redundant and overspecifying. We preferred staying close to (a) the probability of at least one planet and (b) the expected value of the number of planets.
2. Number of CumIHZs searched to TXP sensitivity
   - *Rationale:* Similarly, we want a deeper search of the IHZ; cf. M4 - more CumIHZs fills in the inner planets
3. Minimum brightness of exoplanet that is detectable at angles in the range from 1-2×IWA (TBR).
   - *Rationale:* Ability to see fainter point sources improves the depth of search (cf. M3, M4) and its completeness down to small sizes; also improves characterization by virtue of seeing more of the orbit. Typically δ-mag = 26, but larger δ-mag gets more planets.

Discriminators (full text, 2/5)

4. Number of candidate exoplanets that are confirmed
   - *Rationale:* Establish the capability to do measurements to confirm candidate exoplanets.
   - *Comment:* See definition of "Confirmed." Confirming every exoplanet system could be very demanding for some mission concepts. Relaxing this number may leave many planet candidates unproven until a followup mission.
5. Number of discovered exoplanets characterized by R>4 spectroscopy (color photometry) across the full 0.5-1.0μm
   - *Rationale:* See M5. If there's any limitation or difficulty, it's better to characterize more planets by color.
6. Number of discovered TXPs that can be characterized by R>70 spectroscopy across the full 0.5-1.0 μm
   - *Rationale:* See M6. It's better to characterize more planets for the presence of H_2O, e.g. by having a small IWA. These capabilities also aid the characterization of giant planets outside the HZ.
   - *Comment:* Again, this is a statistical estimate based on distributions and observing scenarios.

Discriminators (full text, 3/5)

7. Number of discovered TXPs characterized by R>70 spectroscopy across 0.5-0.85 µm
   - *Rationale:* See M7. It's better to characterize more planets by O2 even if H2O is inaccessible. These capabilities also aid the characterization of giant planets outside the HZ, e.g. via methane at 728, 793, and 863nm, and water at 830 nm.
   - *Comment:* Again, statistical estimate based on distributions and observing scenarios.
8. Extended passbands to NIR and NUV
   - *Rationale:* Some mission concepts are capable of TXP sensitivity further into the IR or the UV. This can provide more atmospheric absorption bands and other information about the planet and exozodi.
9. Number (or percentage) of found candidate exoplanets for which we can test for common proper motion
   - *Rationale:* See D4 and the definition of "Confirmed." Common proper motion is the gold standard for proving the object is a true companion; some alternatives were listed above.
   - *Comment:* We don't know how many candidates will be detected, so we should not pin ourselves to a fixed number. And in an exoplanet-rich scenario, confirming a minimum percentage may be a challenge.

Discriminators (full text, 4/5)

10. Number of found planets whose orbital SMA can be determined with ±10% uncertainty (TBR) or better.
    - *Rationale:* This may be difficult because of the number of visits required. This depends on agility for multiple revisits, confident detection each time, and accurate planet-star relative astrometry.
    - *Comment:* Perhaps also give credit for even finer SMA determination.
11. Number of TXP masses determined to TBD%
    - *Rationale:* Measurement of the host star's astrometric wobble is the gold standard for exoplanet mass determination. (Indirect methods have been proposed, but are vulnerable to scientific uncertainties.) No existing well-developed mission concepts are believed capable of providing this astrometric information, so there is no Must or minimum requirement for this knowledge. But if we can demonstrate convincingly that one or more concepts could provide this, we should give high scores for that.
12. Number of discovered TXPs characterized by absolute photometry
    - *Rationale:* See M10 – we want more planets characterized by absolute photometry
    - *Comment:* Again, statistical estimate based on distributions

Discriminators (full text, 5/5)

13. Number of giant exoplanet candidates detected in ExoEarth target systems
    – *Rationale:* We want the capability to detect and characterize a variety of giant planets, especially to see if there are correlations between the presence and nature of TXPs and of giant planets. Also establishes the virtue of a large ratio OWA/IWA.
14. Number of Kuiper Belts imaged in ExoEarth target systems
    – *Rationale:* Of course we want to detect many examples of inner and outer debris disks, but we especially want to see if there are correlations between the presence and nature of TXPs and of Kuiper Belts. Also establishes the virtue of a large ratio OWA/IWA.
    – *Comment:* We haven't defined "Kuiper Belt" by a range of characteristics.

Discriminators mapped to Objectives

Discriminators	Science Objectives										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
D1: # CumHZs	✓						✓				
D2: # CumIHZs	✓						✓				
D3: max δ-mag	✓						✓				
D4: # confirmed	✓						✓				
D5: # planets, 4 color			✓	✓				✓			
D6: # planets, full spectra						✓		✓			
D7: # planets, part spectra						✓		✓			
D8: NIR and NUV						✓		✓			
D9: common PM	✓						✓				
D10: # orbit SMA	✓	✓		✓							
D11: # astrometric mass				✓	✓						
D12: # absol photometry			✓	✓							
D13: # giants w/ TXPs							✓	✓			✓
D14: # KuiperB w/ TXPs									✓	✓	✓

Return